NAL CASCODE RF POWER AMPLIFIER

DESIGN DESCRIPTION

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This description supplements the electrical and mechanical drawings of the NAL power amplifier. Contributions to the design have come from the entire RF Section, with major efforts by G. Rees, G. Tool, W. Miller, V. Kelleghan, and J. Rzeczkowski. R. Ducar contributed the Ciran B results.

The electrical and mechanical requirements of the NAL rf power amplifiers derive from two main considerations:

1) The amplifiers are located in the machine enclosure, tightly coupled electrically and mechanically to the rf cavities. (Drawing #0330.00-ME-5021)

2) The amplifier signal path is an integral part of the feedback loop for cavity voltage stabilization.

The first consideration dictates that the amplifier package be compact, and plug-in replaceable. The second consideration dictates a signal delay not over 50 nanoseconds through the amplifier chain, from the 1 watt input port to the 100 kW output connection at the power tube anode.

A block diagram of the amplifer from the 1 watt input to the 100 kW output is shown in Drawing #0330.00-EB-5010. The individual element delays as computed are shown on this drawing and total 41.5 nsec for the complete amplifier over the operating frequency range of 30 to 53 MHz. All of the blocks shown on this drawing, excluding dc power supplies, are contained in a 16 in. diameter by 30.6 in. high cylindrical Iridited aluminum housing shown on Drawing #0330.00-MD-5021. The amplifier can be dismantled into separate modules in the workshop. All connections for water and electrical leads are made to one side of the cylindrical enclosure.

Cooling

Heat generated in the amplifier housing is removed from the individual components and the housing by circulating water. No forced-air cooling is used inside or outside of the housing. Quick-disconnect water connections facilitate rapid removal and replacement of the amplifier. Copper tubing water circuits at different rf and dc levels within the amplifier are coupled together with insulators of 99% alumina ceramic tubing with brazed copper ends. An adequate supply of low-conductivity water (2 megohm-cm) is available.

Amplifier Maintenance

Amplifier maintenance operations in the accelerator enclosure will be limited to removal of a defective amplifier and replacement with a tested unit. The entire cycle of removal and replacement should be as simple and direct as possible. Marman clamps and quick-disconnect hose fittings are used to speed the replacement process.

An amplifier that has been removed from accelerator service will be transported to a suitably-equipped repair center where working space, tools and full test equipment are available. At this repair center, the amplifier will be dismantled into its respective sub-assemblies to permit pinpointing the defect, replacement, and sub-assembly checkout. After reassembly, the complete amplifier package will be exercised on a test facility and after checkout returned to stock as a spare amplifier.

RF Level Modulation

The amplifier output power level to the cavities must be programmed. Accelerator requirements necessitate an anode current control range in the power tube of approximately 10 to 1. To achieve the proper current, more than one variable must be controlled. The applied rf amplitude at the 1 watt input port will be programmed. In addition, provision is made for adjusting the operating point (bias) of the 100 kW power output tube continuously during the accelerating cycle. Such adjustment is provided by variation of grid bias to the fourteen 4CW800F tetrodes, whose combined average plate current is equal to the output stage cathode current. Because this method takes advantage of the dc gain of the 4CW800F tetrodes, the output tube operating point can be modulated through its full range with approximately 30 volts. The anode dc supply voltage is obtained from a modulator whose voltage output will be varied to follow the rf envelope at the power tube anode.

Monitoring

During accelerator operation, the rf level at indicated points in the amplifier will be monitored via coaxial connectors provided on the amplifier housing. Individual tube dc currents in the amplifier are available for specialized monitoring at the repair center. Total currents fed from power supplies located outside the machine enclosure can be monitored during operation. Monitor points are shown on the schematic drawings.

Amplifier Design

Details of the various blocks shown on drawing 0330.00-EB-5010 are indicated on the following drawings:

No.	Title
0330.00-EC-5011	Cascode Power Amplifier Distributed Amplifier-Schematic
0330.00-EC-5012	Distributed Amplifier Output Transformer-Schematic
0330.00-EC-5013	Cascode Power Amplifier Driver-Schematic
0330.00-EB-5014	Cascode Power Amplifier Coupling Network and Output Stage-Schematic

Distributed Amplifier

The first stage of the 100 kW amplifier is a six tube distributed amplifier (Drawing #0330.00-EC-5011) contained in the uppermost module. The six water-cooled Eimac 4CW800F power tetrodes are located 45° apart on a 12 in. diameter circle. Electrically they are incorporated in the usual manner into grid and anode transmission lines. A ferrite-core transformer matches the 50 ohm input cable to the 25 ohm grid line impedance at the 1 watt input level. Both the grid line and the 280 ohm anode line are bridged-T networks. The cut-off frequency of the grid and anode lines is approximately 200 MHz, and the time delay through the amplifier is 18.5 nsec.

The linear circuit equivalent of the amplifier has been analyzed using the computer program CIRAN B. The amplitude, phase and delay of the voltage transfer function are shown as plotted by the computer in figures 1, 2 and 3 respectively for several choices of m.

A power gain of 100 is achieved with the following operating parameters: (voltages referred to cathode)

dc Anode Voltage	600 V
dc Screen Voltage	275 V
dc Anode Current (each tube)	.5 A
Transconductance gm	40 mmho
Total anode dissipation	1800 W

A resistor in series with each cathode provides grid to cathode bias and equalizes the individual tube's contribution to the total 3A dc anode current. The common side of each of the cathode resistors is brought to a terminal block on the side of the amplifier housing to allow individual monitoring of the dc currents when testing the amplifier. During normal operation, only the total current is monitored. Hollow ceramic tubes complete the water circuit between the anode line and the other heat generating components in the amplifier.

D.A. Output Transformer

A ferrite core transformer connects the single 288 ohm anode transmission line to each of the 14 - 50 ohm input connections of the cascode power amplifier driver (Drawing #0330.00-EC-5012). This transformer is located at the same elevation in the housing as the distributed amplifier, but is mechanically supported on the cascode driver module. Separation of the distributed amplifier and cascode driver modules involves disconnecting the single primary input rather than the 14 secondary outputs. The transformer floats at the -1500 V dc potential of the cascode driver input circuit. Signal delay through the transformer is 7.25 nsec. A separate winding on the transformer allows monitoring of the drive level.

Cascode Driver

The 14 output cables of the coupling transformer drive 14 parallel Eimac 4CW800F power tetrodes. Their anodes are in series with the cathode of a grounded-grid Eimac 4CW100,000E output tube. The 14 driver tubes, their input circuits and a filament transformer which provides filament power through individual secondary windings for all 20 4CW800F tubes (6 in distributed amplifier, 14 in cascode driver) are mounted in a second demountable module directly below the distributed amplifier. The input capacitance of each of the driver tubes is transformed to a 50 ohm resistance by a separate bridged-T, all-pass, M-derived section (Drawing #0330.00-EC-5013). The 14 tubes are mounted in two concentric circles, the inner one containing 4 tubes and the outer one containing 10 tubes. As in the distributed amplifier, all screens are tied together on a conducting plane. This plane, which is bypassed to ground by a ring of 10 kV capacitors on which it mounts, serves as the isolating ground plane between driver input and output circuits. The individual tube currents are equalized by a series 100 Ω resistor in each of the 14 cathodes. The return wires are brought to a common terminal block on the side of the module to allow individual monitoring during testing and total current monitoring during operation. Each cathode is bypassed to the ground plane by a ring of ceramic capacitors around the tube base. The individual 50 ohm gfid termination resistors and the 100 ohm cathode resistors mount on a water-cooled heat sink operating at the power supply voltage of -1500 V dc.

Cascode Coupling Network

The anode circuit of the 14 driver tubes has a total shunt capacitance of 118 pF, and the grounded-grid input circuit of the 4CW100,000E has a capacitance of about 250 pF (varies with plate current in range 215 - 270 pF) when filament power is on. This capacitance is in shunt with $1/g_m$ (15 to 30 ohms) of the output tube. To provide suitable frequency response in the range 30 - 53 MHz, a lossy series inductor (L = 75 nH, Q = 3 @ 50 MHz) has been inserted between the 14 common anodes and the power tube cathode (Drawing #0330.00-EB-5014).

Coaxial geometry is achieved by forming the inductor of five 5 in. o.d. by 3 in. i.d. by 1/2 in. thick powdered iron toroids clamped between water-cooled copper plates (Drawing #0330.00-MD-5021). The response (power tube cathode-grid voltage/driver current) is essentially flat in amplitude and linear in phase in the frequency range 30 - 53 MHz. Associated with this response, there is a rising driver anode voltage vs. frequency characteristic. The sandwich of inductor toroids and copper cooling rings is held in compression by a nut threaded on the center conductor. The upper end of this assembly connects to the 14 anodes and the lower end attaches to the cathode ring of the power tube. On removing the driver module, the spring finger anode connections is opened; the inductor assembly remains as part of the output tube assembly.

Power Output Tube

The Eimac 4CW100,000E output tube is mounted in a modified socket with its control grid tied directly to the housing shell through a grounding cone. This cone supports the water-cooled cathode plate and lossy inductor assembly. The screen ring is by-passed and spark-gap protected to this ground cone. The power tube is held into the socket by the Eimac locking device actuated from the top through a cylindrical hole down the center of the amplifier assembly. The filament of the tube is powered by an electrostatically-shielded toroidal filament transformer which surrounds the tube base and is connected to the filament through four rf chokes.

The anode circuit of the power tube connects to the accelerating cavity through a ring of 12 blocking capacitors. When the anode connection is released, the blocking capacitor assembly and the anode dc supply lead remain as part of the cavity. Water is connected to the anode water jacket via alumina ceramic tubes.

Power Supplies

A listing of required power supplies is given on Fig. 4 and its accompanying table, Fig. 5. Fig. 6 shows rack panel sizes for commercial power supplies as a guide to indicate maximum total power supply cabinet size. It is advantageous to reduce the power supply cabinet size to less than the maximum dimensions.

Circuit Analysis

Attached are interpreted results of a computer analysis of the Power Amplifier. The Ciran B program was used to obtain Gain, Phase and Delay vs. Frequency responses. Linear models of the various parts of the amplifier were developed. Parameter changes occuring in the frequency range are not accounted for in the analysis.

Due to program limitations, the amplifier circuit had to be segmented. Overall response curves were developed from summation of data from the individual circuit blocks.

The Power Amplifier circuit was divided up in the following manner:

CCT #1	50 to 25.5 Ω Distributed Amp Input Matching Transformer
CCT #2	Distributed Amplifier
CCT #3	Distributed Amplifier Output Matching Transformer
CCT #4	Cascode Amplifier and Power Tube

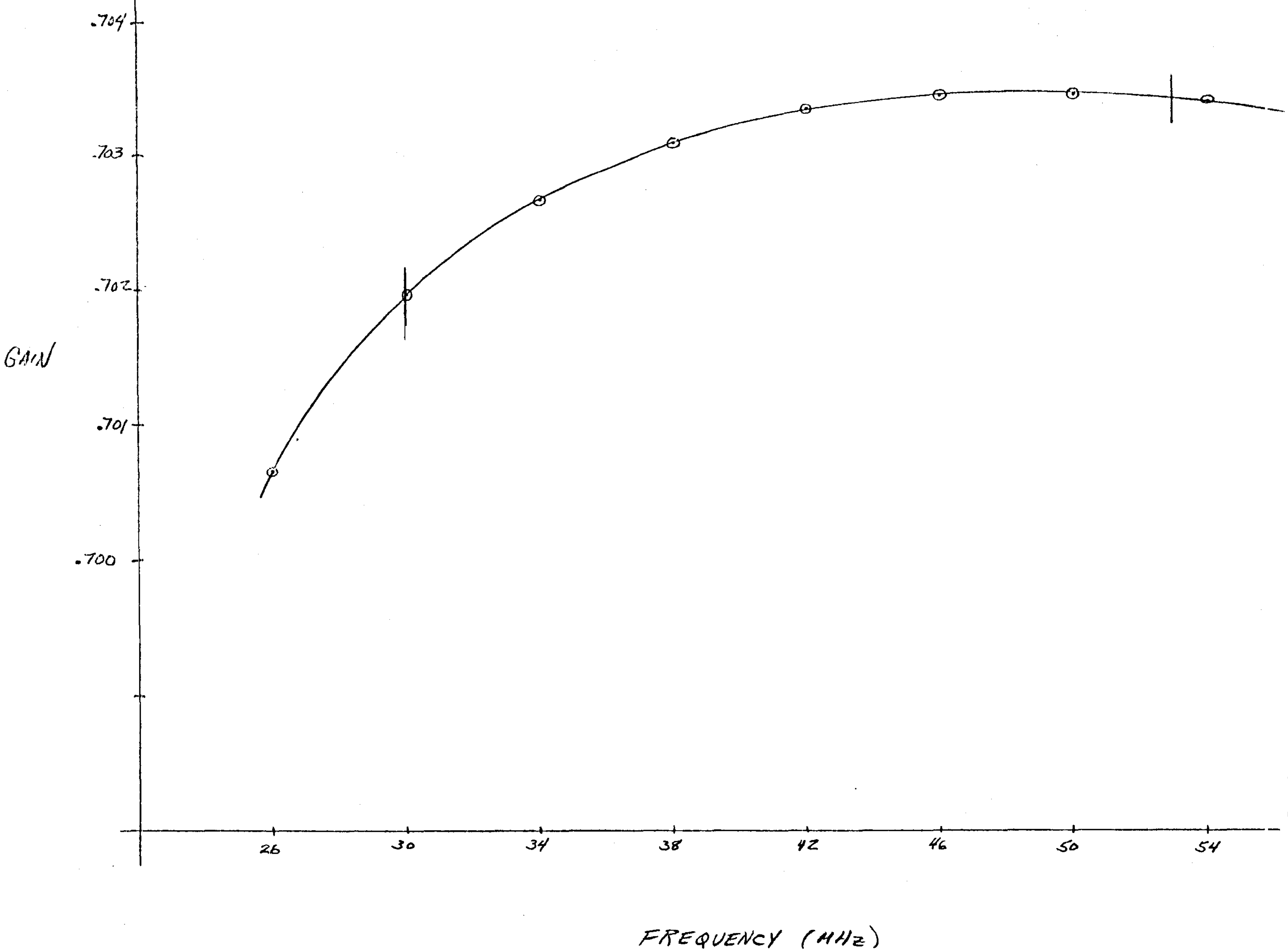
One stage of the DA was analyzed and results projected for the 6 stage DA package. The curves for the DA and Cascode Amp areain envelope format to reflect the range of response dependent upon choice of the "m" factor in the "m"-derived filter used in each of these circuits.

The Misc. Flat delays are averaged values and added to the responses of each circuit where applicable. Linear phase shifts due to the flat delays are also added to the responses according to the formula:

$$\phi(w) = \int_{0}^{\Omega} \tau dw \Bigg| \quad \phi(0) = 0$$

50 to 25.5 Ω MATCHING XFORMER

GAIN RESPONSE CURVE



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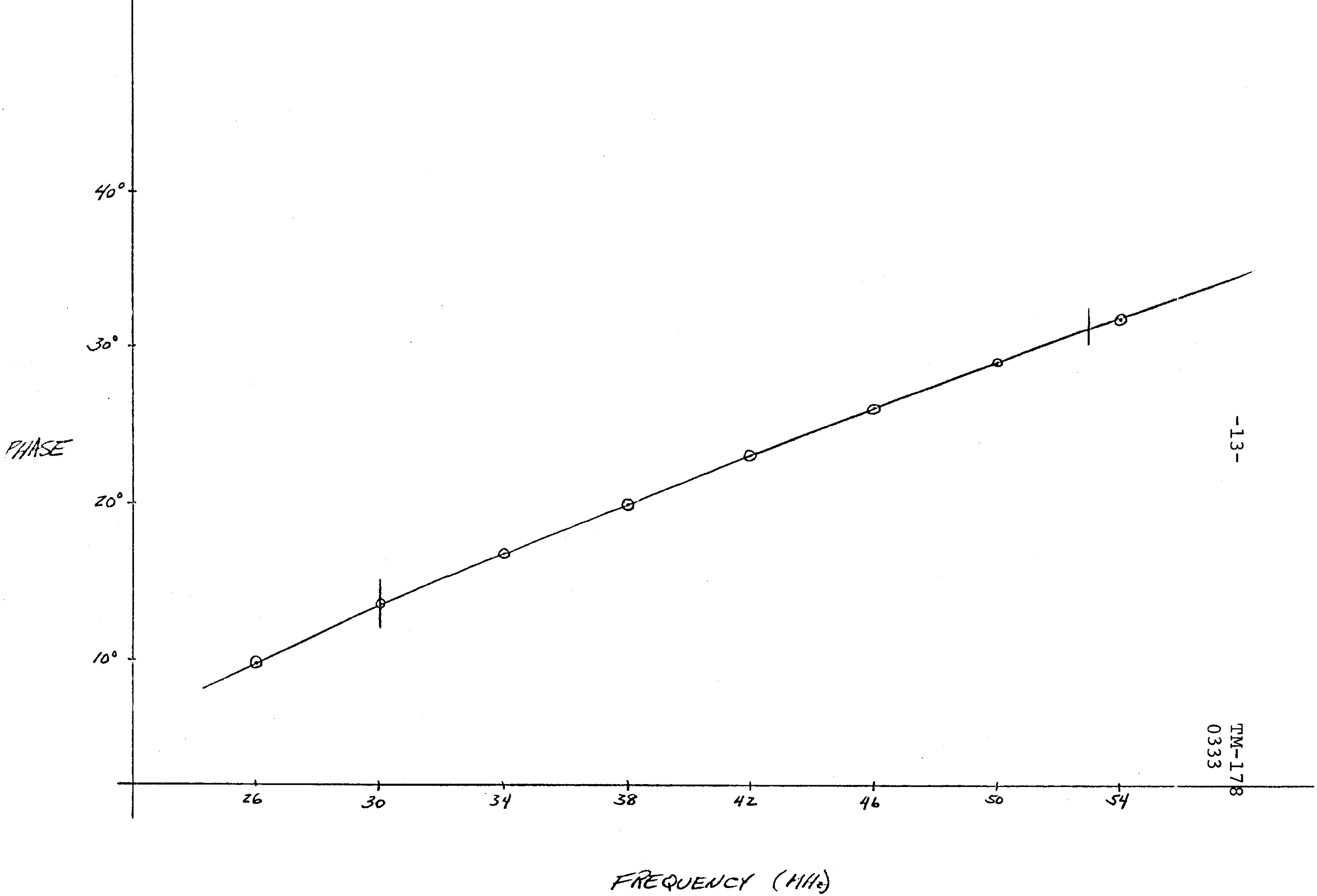
50 to 25.5Ω MATCHING XFORMER

PHASE RESPONSE CURVE



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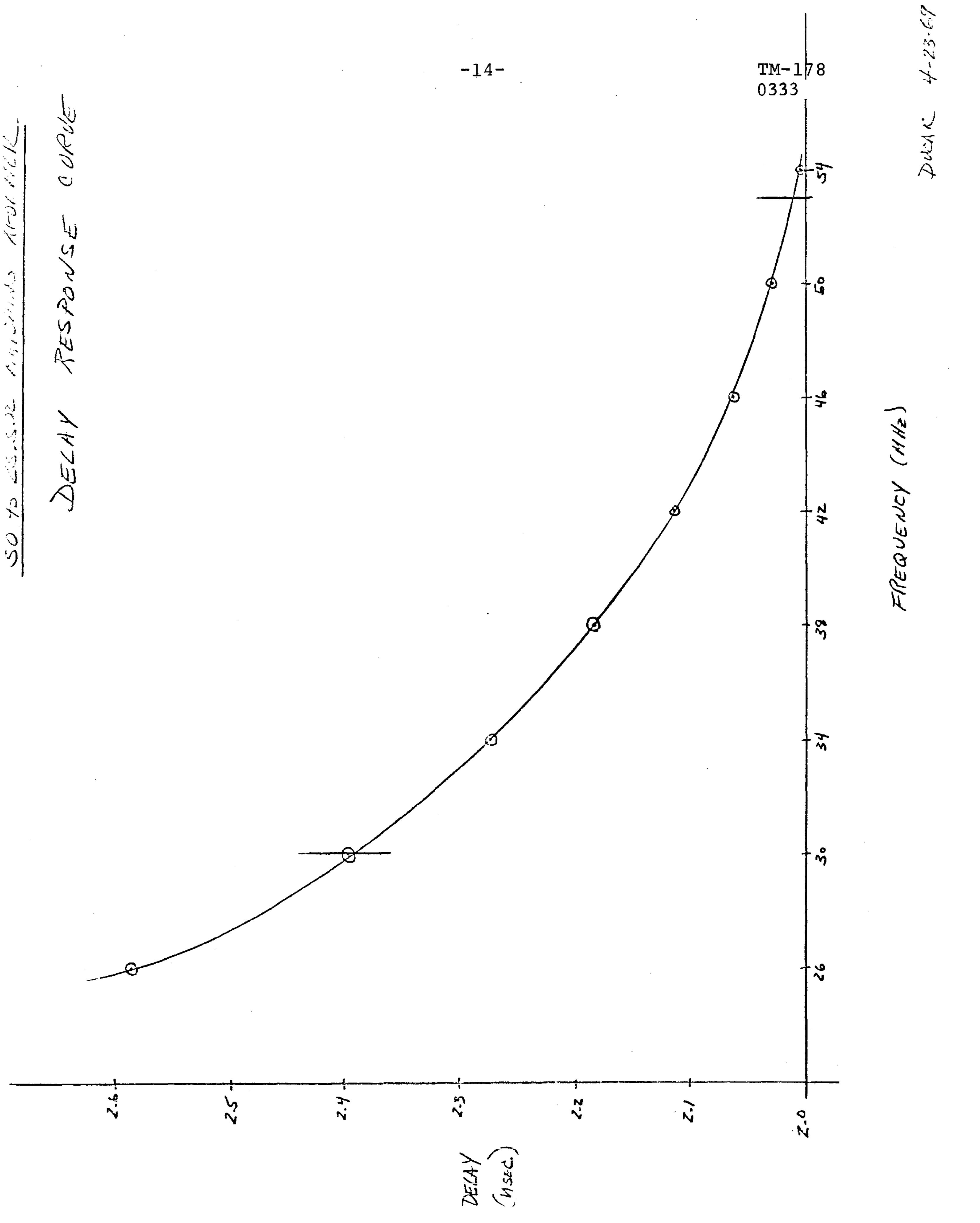
DELAY RESPONSE CURVE
FREQUENCY (MHz)
DELAY (μsec)
2.6
2.5
2.4
2.3
2.2
2.1
2.0
26
30
34
38
42
46
50
54
4-23-69

DA INPUT XFORMER 50Ω to 25.5Ω

CABLE DELAY
1.5

.700685	-4.1771	1.0846	+9.8629	2.5846	14.04
.70194	-2.7597	.89722	+13.4403	2.39722	16.2
.702657	-1.5641	.77117	+16.7959	2.27117	18.36
.7031	-.52104	.68236	+19.99896	2.18236	20.52
.703357	+.41251	.61745	+23.0925	2.11745	22.68
.703457	+1.2649	.56858	+26.1049	2.06858	24.84
.703471	+2.0553	.53086	+29.0553	2.03086	27.0
.7034	+2.7976	.50113	+31.9516	2.00113	29.16

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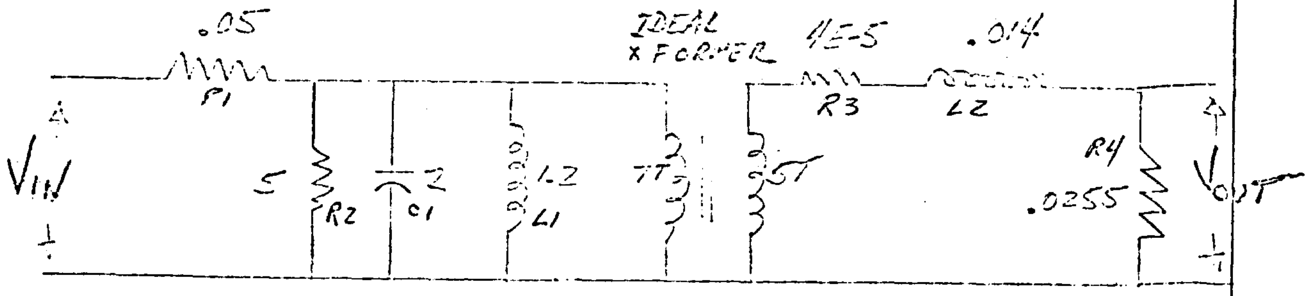
MATCHING XFORMER RESPONSE

UNITS — KΩ, μH, pF



$$W_{ant} - \frac{V_{out}}{V_{IN}/2} \text{ + PHASE } \Big\} \text{ 1 MHz to 1 GHz}$$

$$\frac{N_1}{N_2} = \frac{7}{5} = 1.4 = a$$

$$a^2 = \frac{49}{25} = 1.96$$

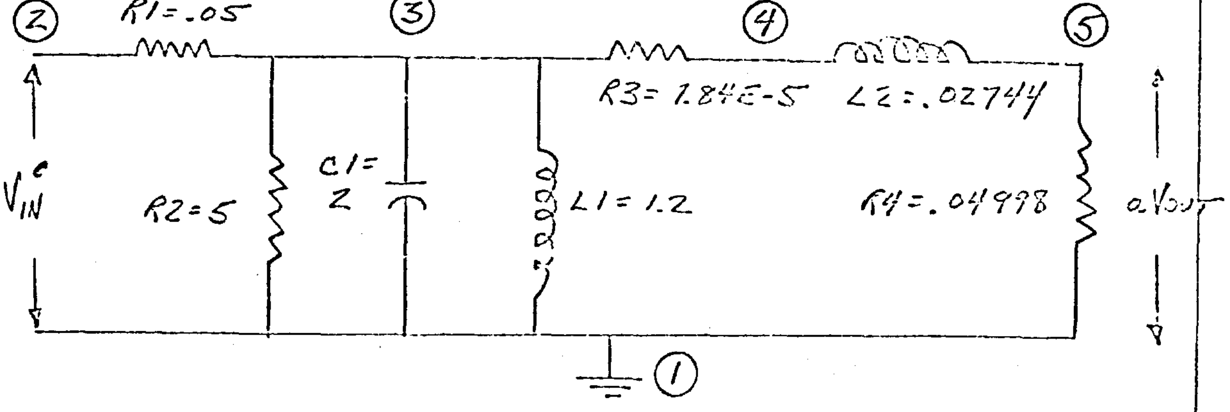
R3 / $a^2\, 4E\text{-}5 = 7.84E\text{-}5$

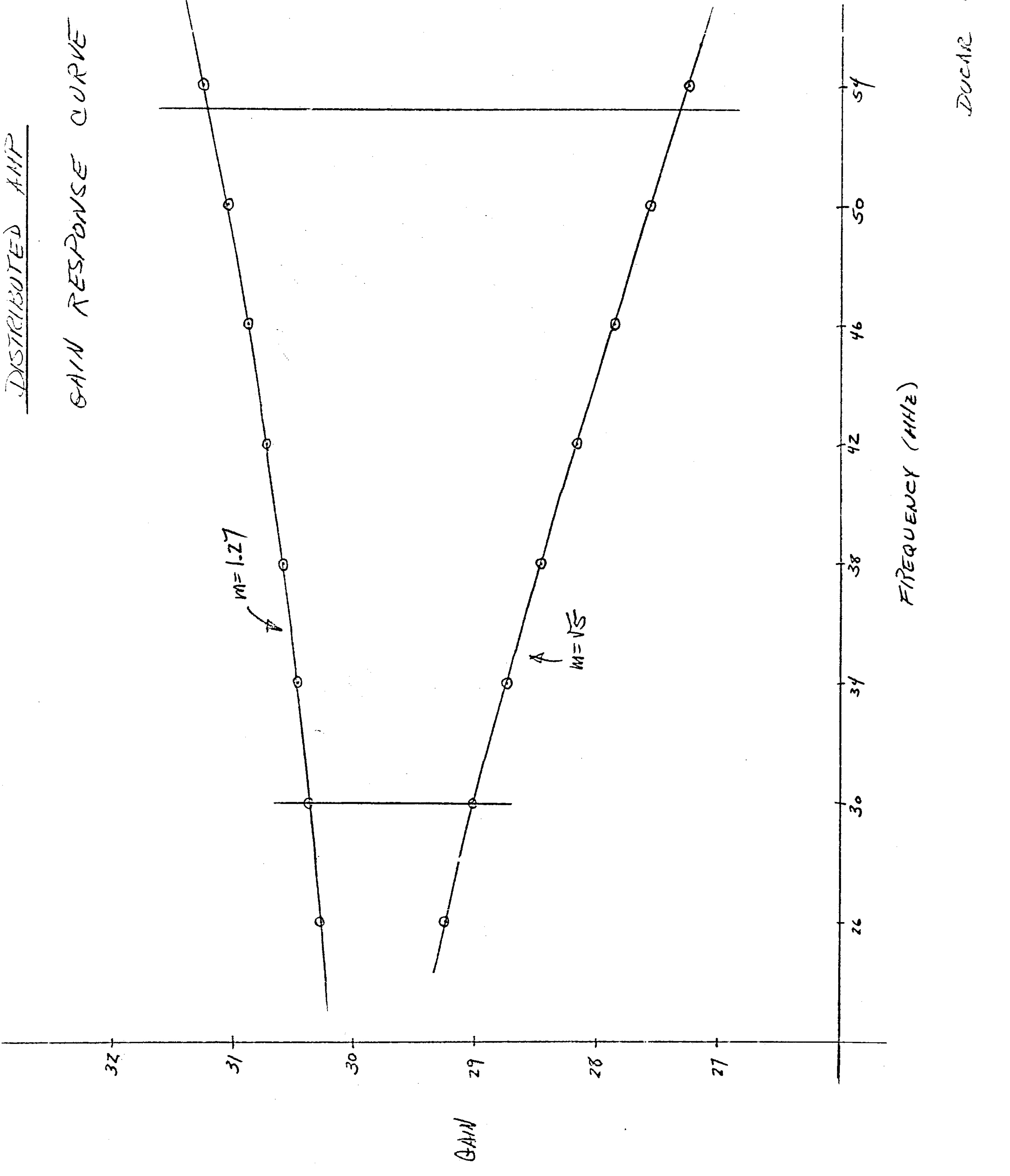
L2 / $a^2\, .014 = .02744$

R4 / $a^2\, .0255 = .04998$

$V_{out} \Rightarrow a\, V_{out}$

THE COMPUTER CCT IS AS FOLLOWS:




DISTRIBUTED AMP
GAIN RESPONSE CURVE
m=1.27
m=√5
FREQUENCY (MHz)
GAIN
26
30
34
38
42
46
50
54
27
28
29
30
31
32
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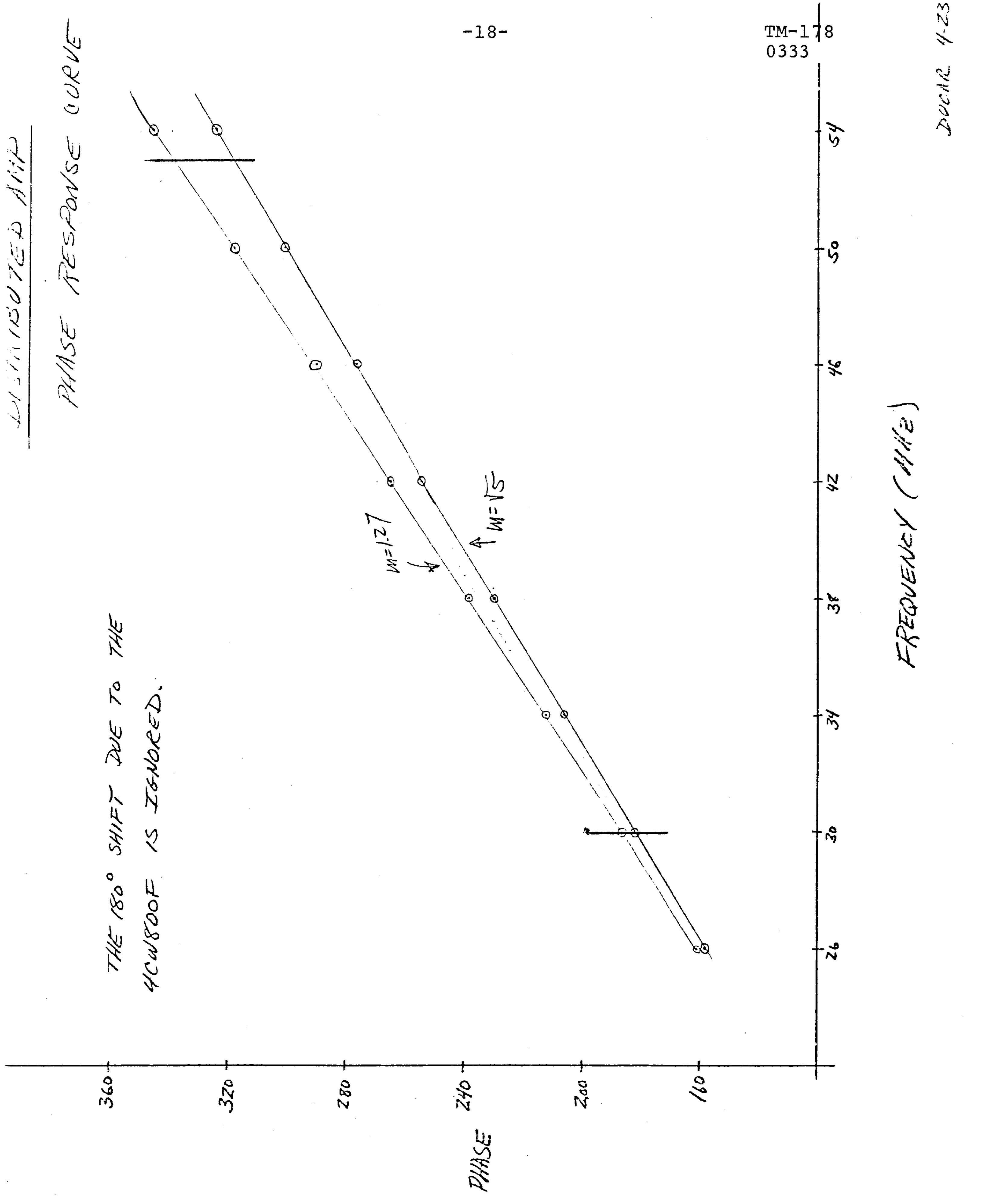
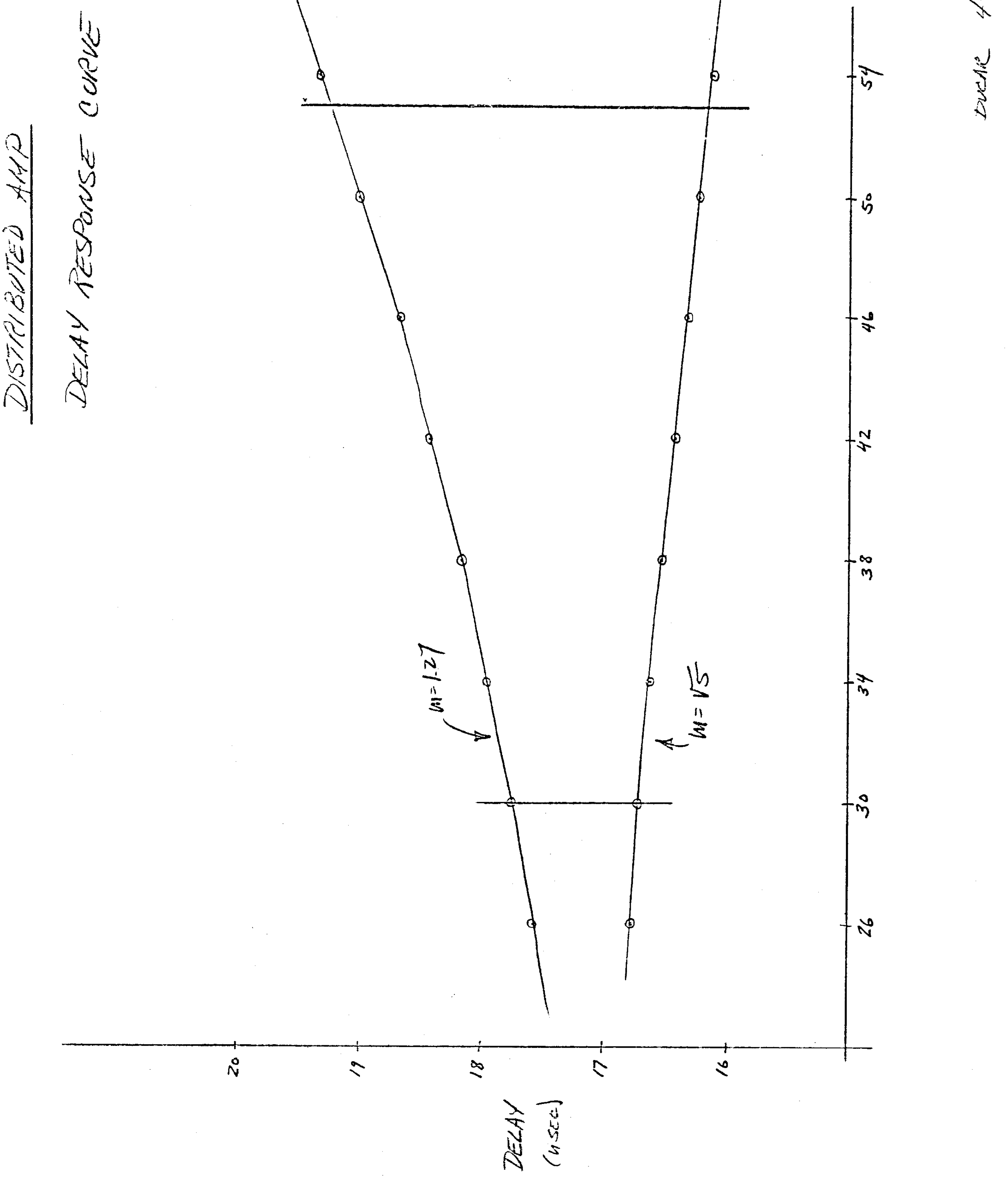

DISTRIBUTED AMP
PHASE RESPONSE CURVE
THE 180° SHIFT DUE TO THE
4CW800F IS IGNORED.
W=1.27
360
320
280
240
200
160
PHASE
26
30
34
38
42
46
50
54
FREQUENCY (MHz)
DUCHAR 4-23-67


DISTRIBUTED AMP
DELAY RESPONSE CURVE
m = 1.27
m = √5
DELAY (μsec)
20
19
18
17
16
26
30
34
38
42
46
50
54
4-23-69

DISTRIBUTED AMPLIFIER

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TIME OF FLIGHT

Z

m=1.27	30.289937	142.332	15.5783	161.05	17.5783	18.72
m=√5	29.258622	139.784	14.7962	158.501	16.7962	
m=1.27	30.388525	164.887	15.7541	186.487	17.7541	21.6
m=√5	29.030103	161.132	14.7167	182.732	16.7167	
m=1.27	30.484611	187.716	15.9556	212.196	17.9556	24.48
m=√5	28.763463	182.265	14.6298	206.745	16.6298	
m=1.27	30.604386	210.858	16.1827	238.218	18.1827	27.36
m=√5	28.484622	203.257	14.5359	230.617	16.5359	
m=1.27	30.745643	234.339	16.4365	264.759	18.4365	30.42
m=√5	28.195535	224.122	14.4366	254.542	16.4366	
m=1.27	30.90119	256.21	16.694	287.33	18.694	33.12
m=√5	27.886558	244.833	14.3342	277.953	16.3342	
m=1.27	31.099122	282.498	17.0273	318.498	19.0273	36
m=√5	27.582357	265.401	14.2307	301.401	16.2307	
m=1.27	31.310787	307.262	17.3676	346.142	19.3676	38.88
m=√5	27.277401	285.824	14.1283	324.704	16.1283	

DA 1 STAGE CCT DIAGRAM

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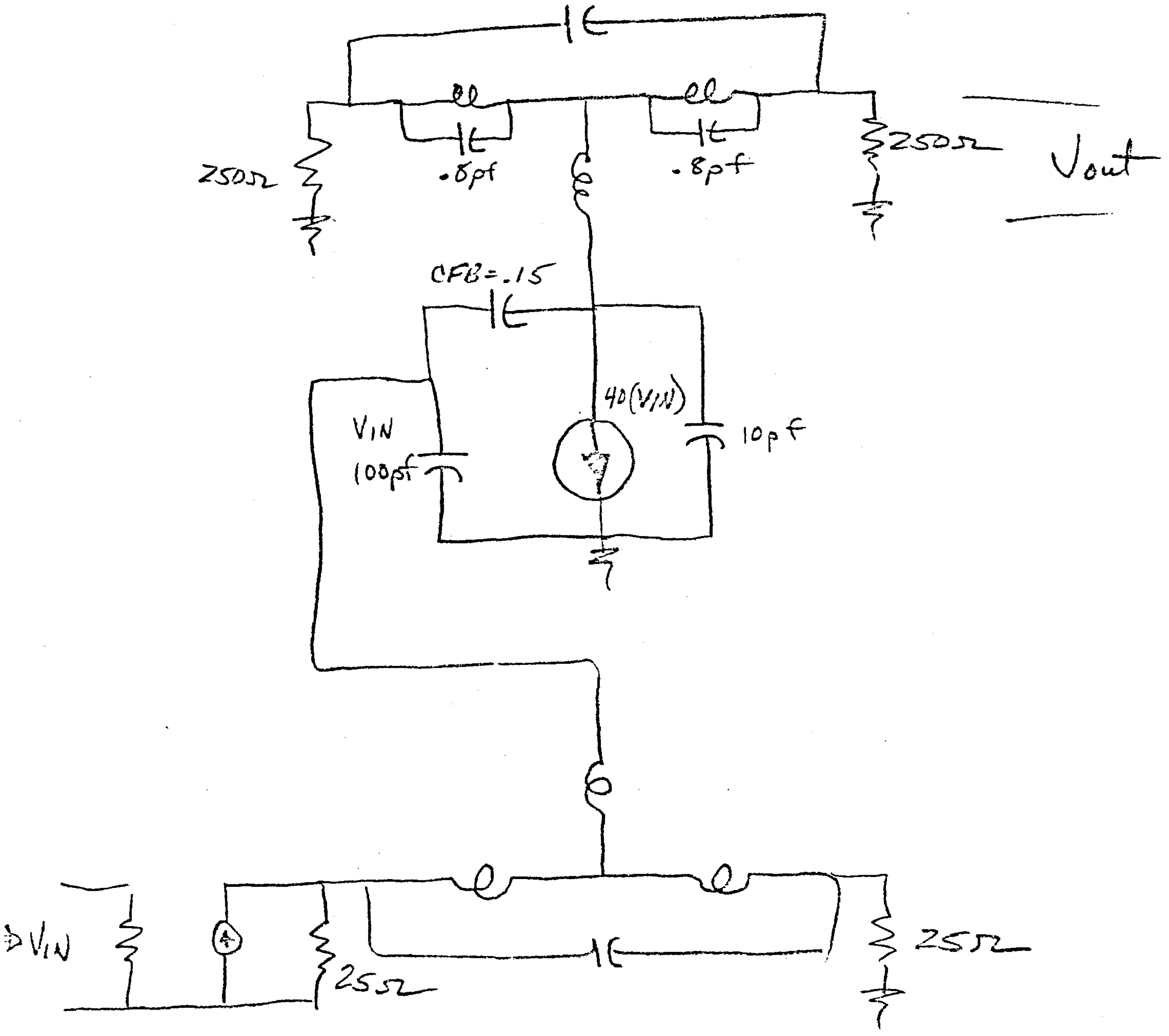
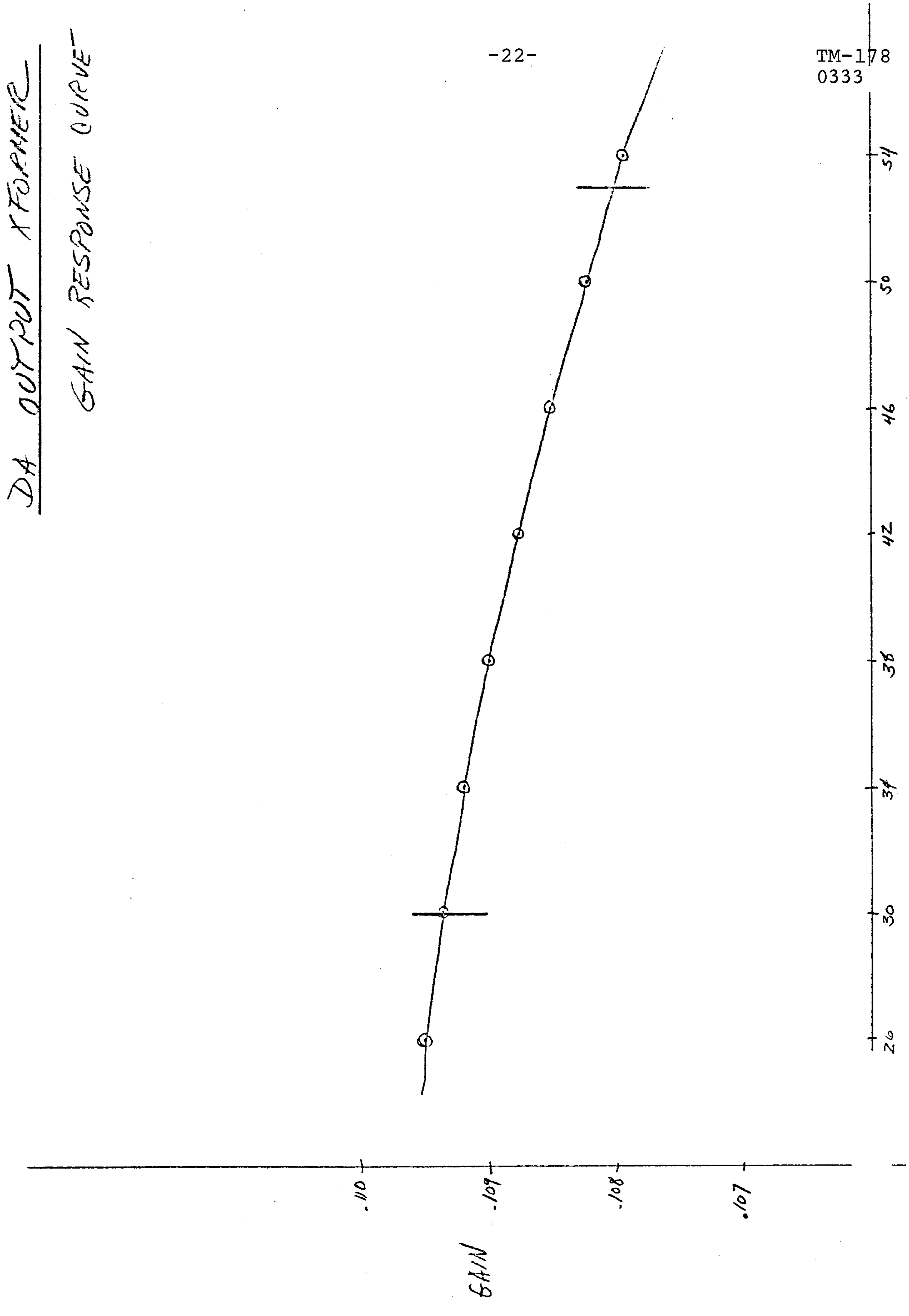
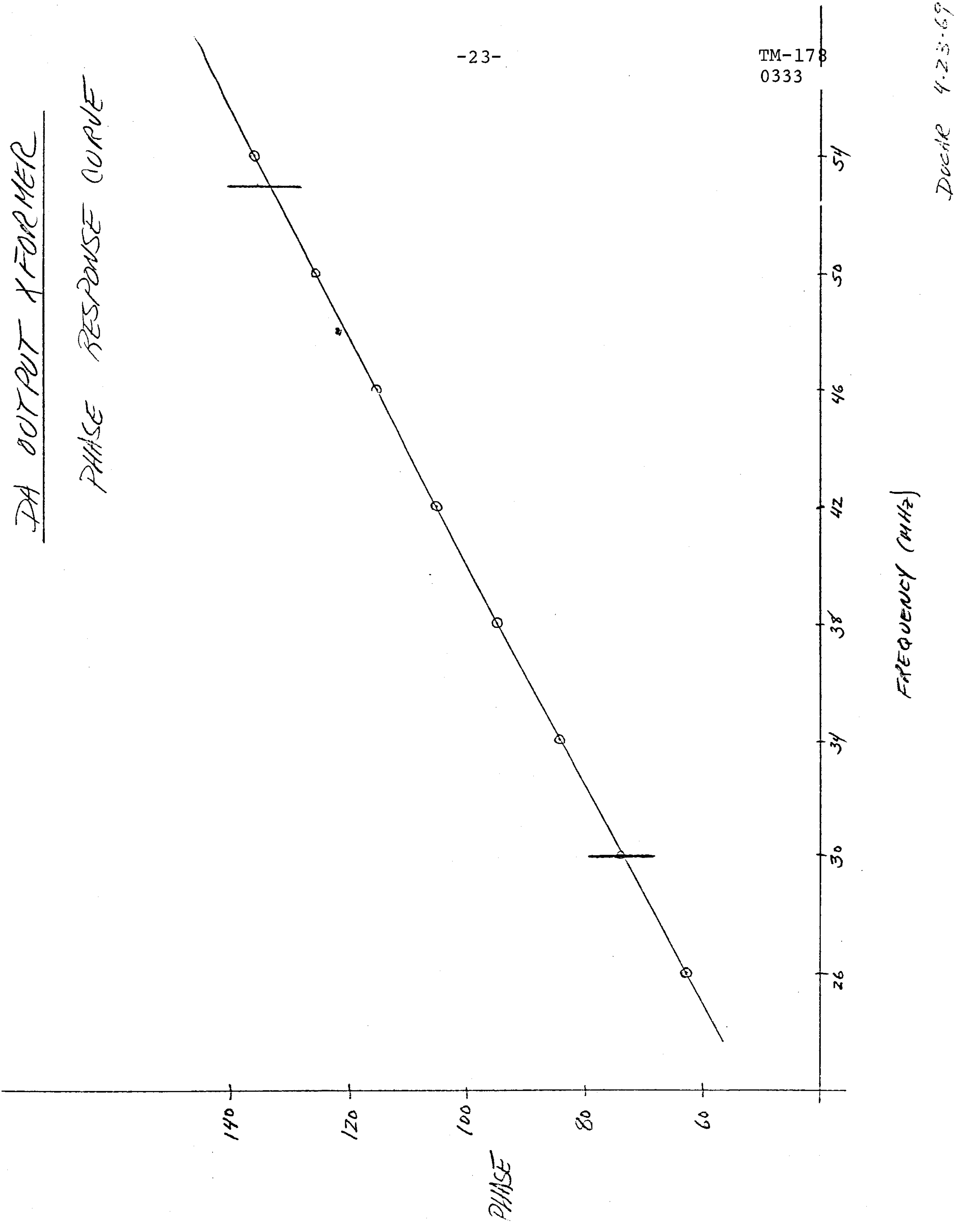
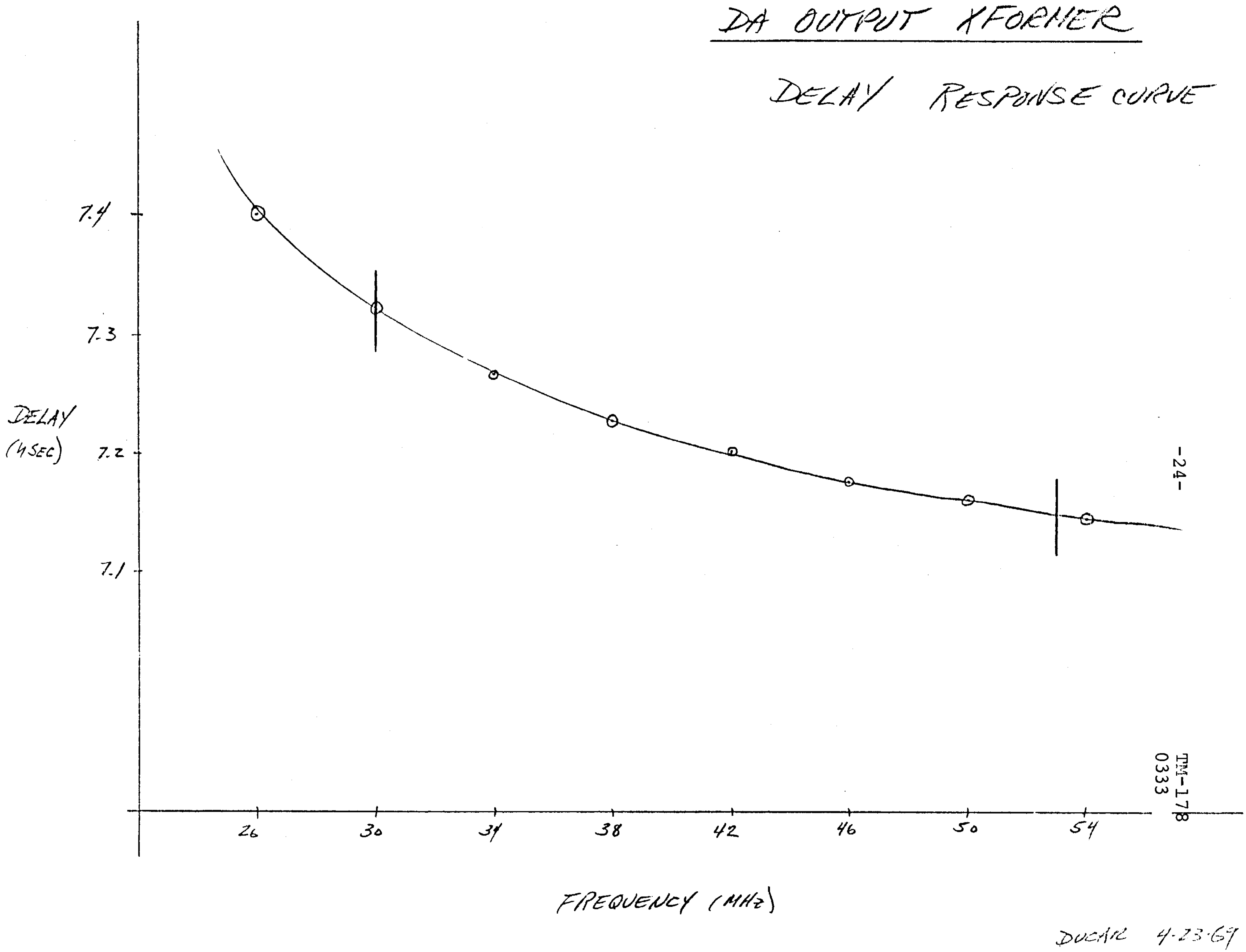



DA OUTPUT XFORMER
GAIN RESPONSE CURVE
GAIN
.110
.109
.108
.107
26
30
34
38
42
46
50
54


DA OUTPUT XFORMER
PHASE RESPONSE CURVE
PHASE
140
120
100
80
60
FREQUENCY (MHz)
26
30
34
38
42
46
50
54


DA OUTPUT XFORMER
DELAY RESPONSE CURVE
DELAY
(μSEC)
7.4
7.3
7.2
7.1
26
30
34
38
42
46
50
54
FREQUENCY (MHz)
DUCAR 4-23-69

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DA OUTPUT XFORMER 297 to 50Ω

CABLE DELAY
6.5

.109507	+2.6636	.90092	+63.5036	7.40092	60.84
.109371	+3.9003	.82213	+74.1003	7.32213	70.2
.109202	+5.0433	.76856	+84.6033	7.26856	79.56
.109	+6.1209	.7301	+95.0409	7.2301	88.92
.108772	+7.1506	.70122	+105.4306	7.20122	98.28
.10852	+8.1435	.67866	+115.7835	7.17866	107.64
.108243	+9.1072	.66042	+126.1072	7.16042	117
.107945	+10.047	.64521	+136.407	7.14521	126.36

PUBLIC

DA Output Matching X Former

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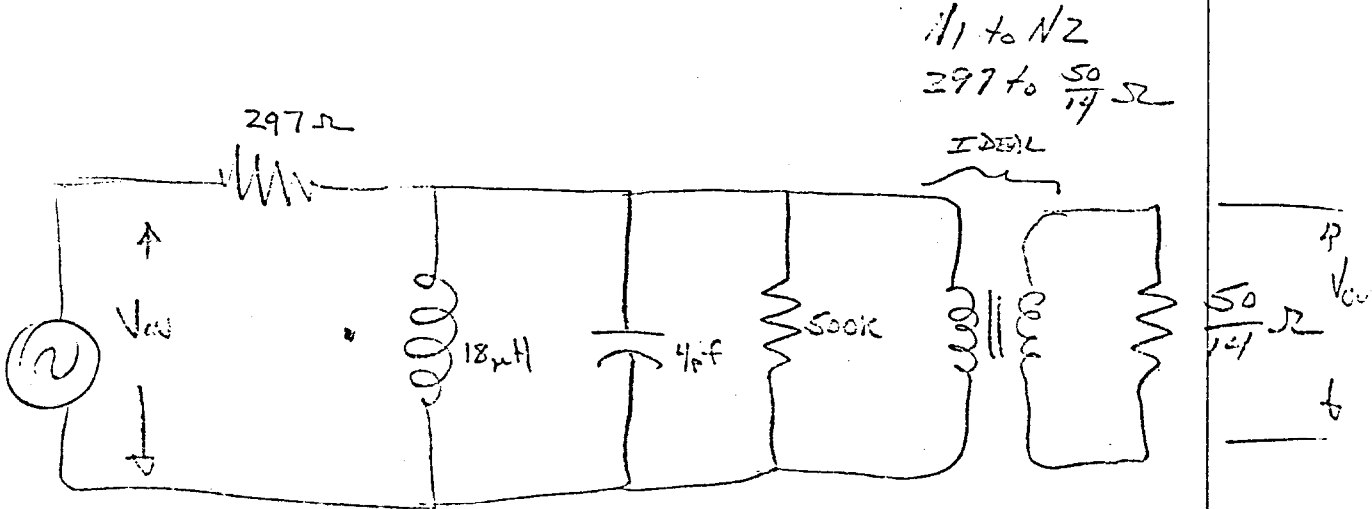


Want : $\frac{2\ V_{out}}{V_{IN}}$ + phase + Delay plots (CIBHU)

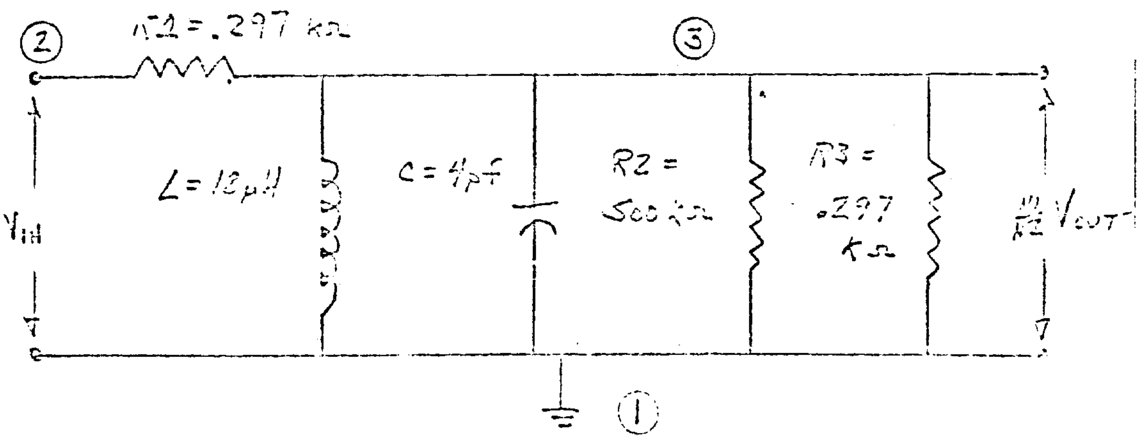
$\frac{50}{14} = 3.571428$

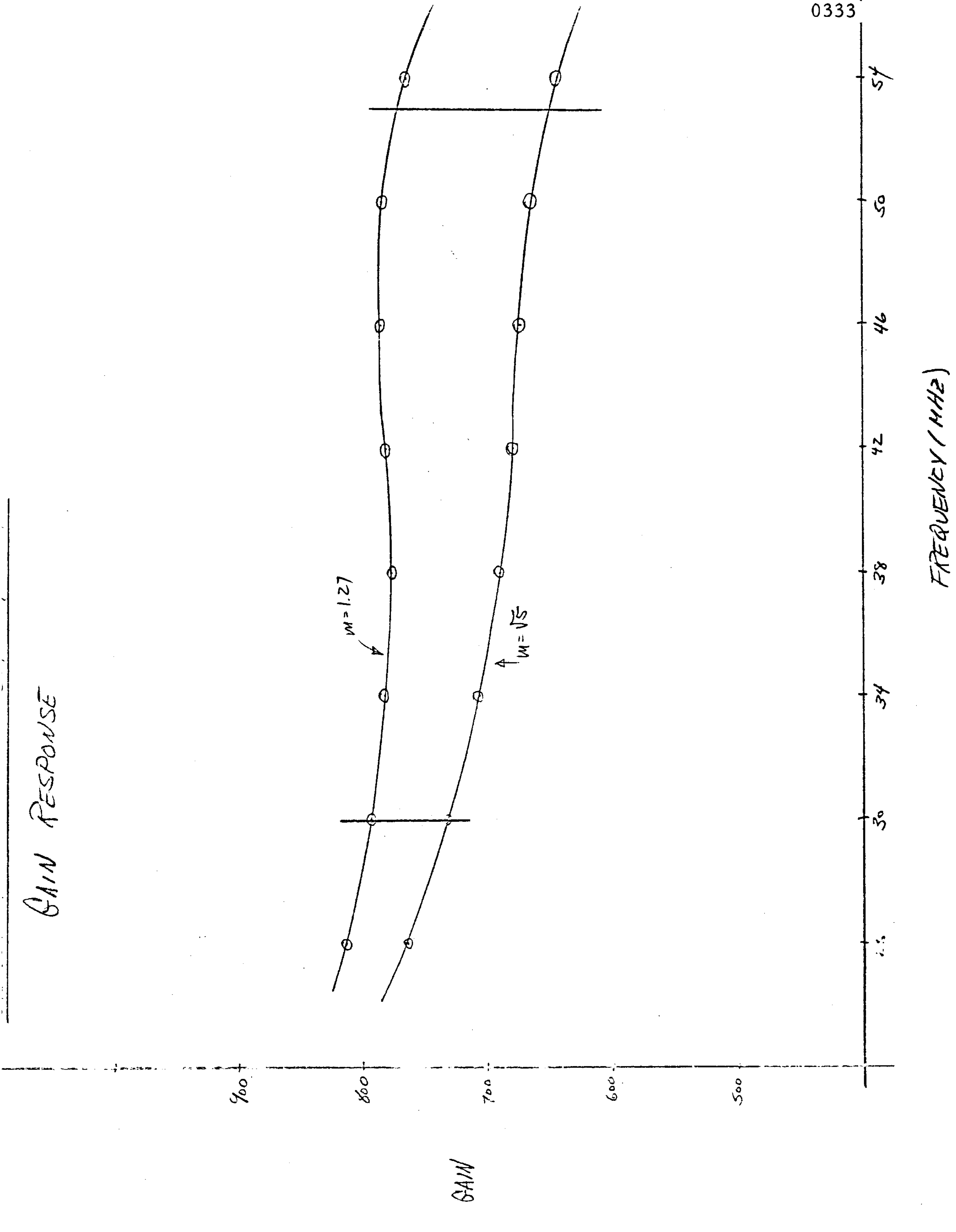
$\left(\frac{N1}{N2}\right)^2 = \frac{297}{3.571428} = 83.16001$ $\qquad \frac{N1}{N2} = a$

$\frac{N1}{N2} = 9.11921$

$\left(\frac{N1}{N2}\right)^2 \times \frac{50}{14} = 297\ \Omega$ $\qquad I_{OUT} \Rightarrow \frac{N1}{N2} V_{OUT}$

THE COMPUTER CIRCUIT IS AS FOLLOWS




GAIN RESPONSE
m = 1.27
m = √5
900
800
700
600
500
GAIN
30
34
38
42
46
50
54
FREQUENCY (MHz)

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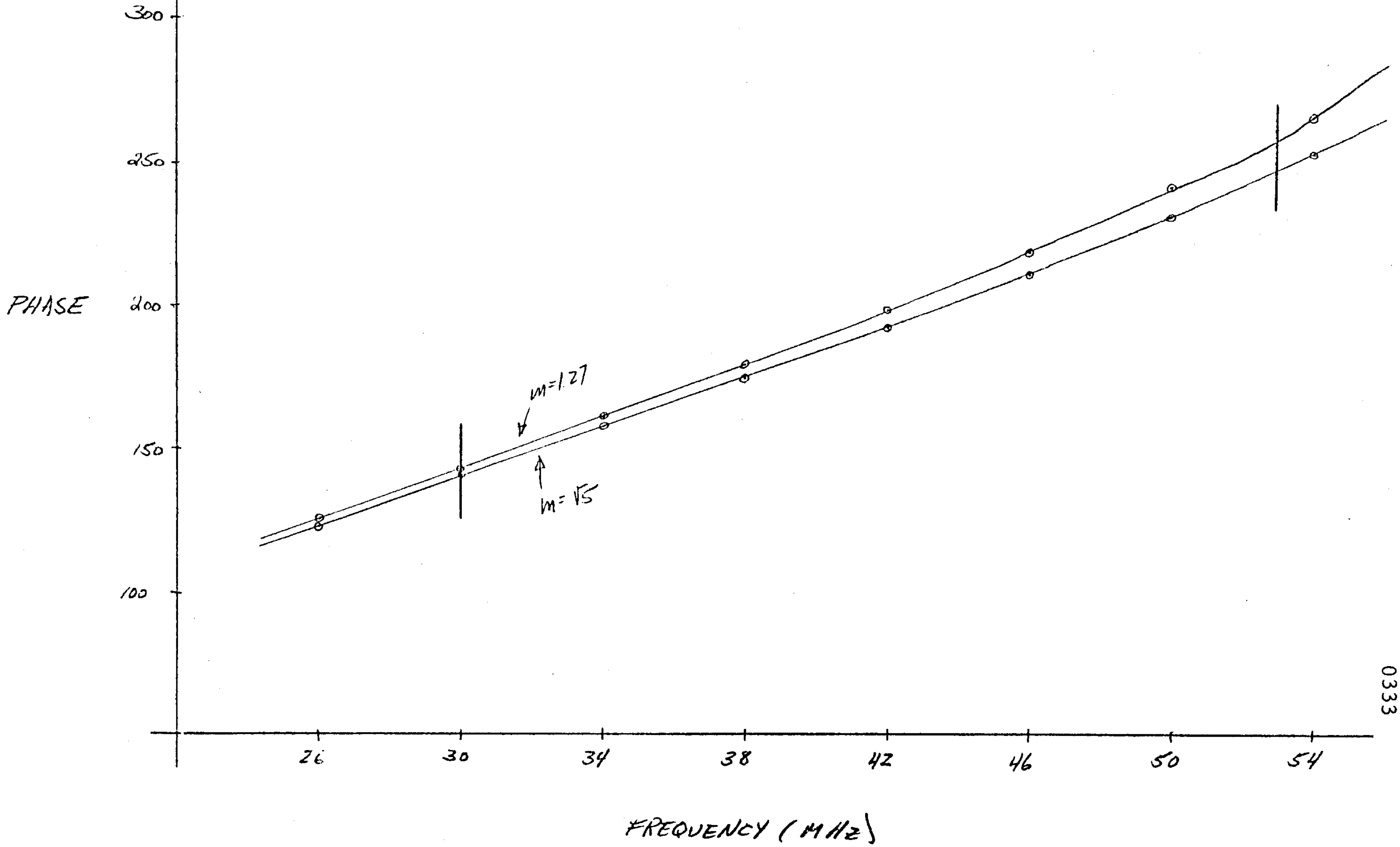
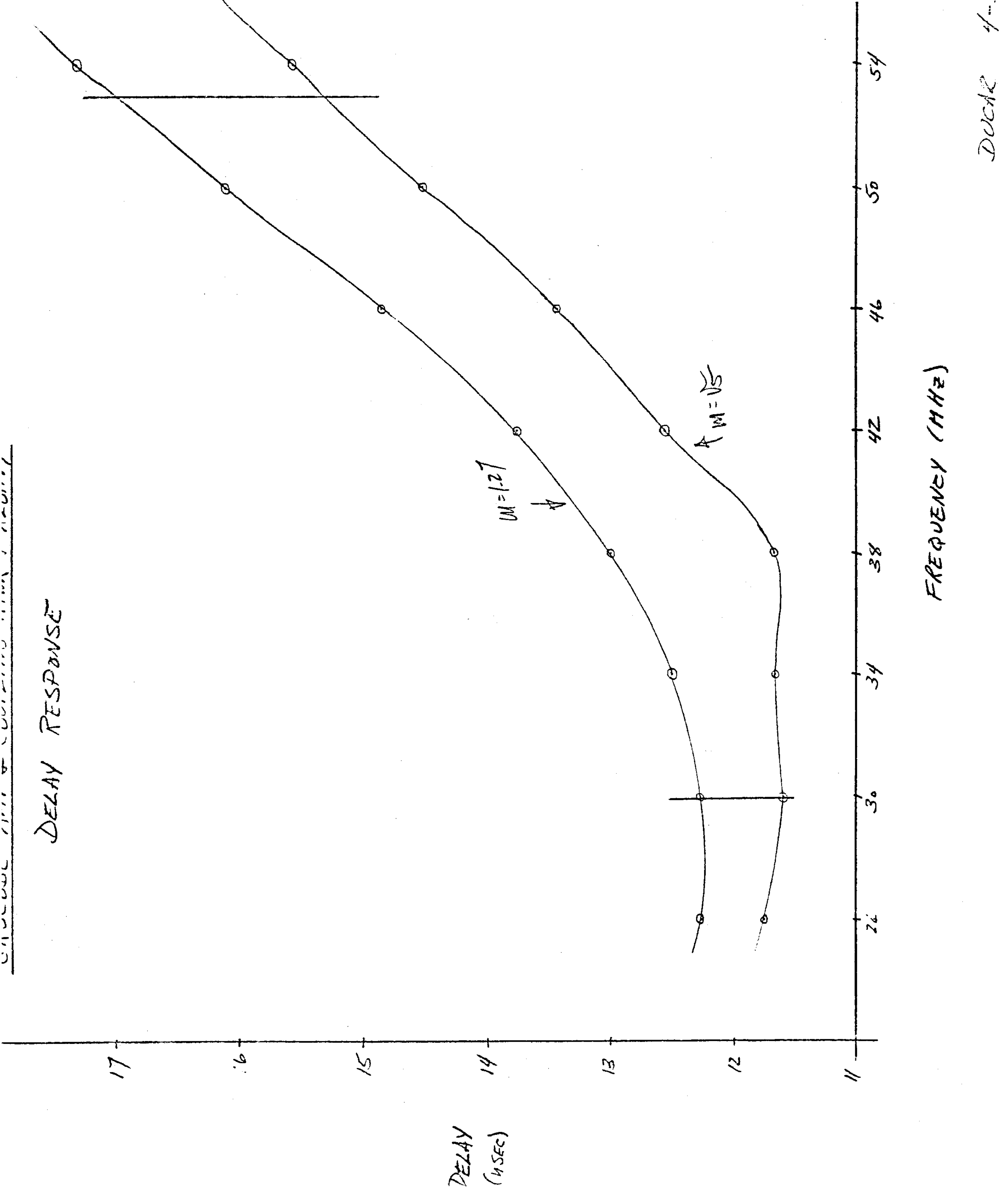
PHASE RESPONSE

PHASE SHIFT THROUGH TUBE IGNORED



DUCAR 4-30-69


DELAY RESPONSE
DELAY (nsec)
FREQUENCY (MHz)
m=1.27
m=√5
11
12
13
14
15
16
17
26
30
34
38
42
46
50
54
DUCAR 1-30-69

R F AMP RESPONSE

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CIRCUIT: CASCODE AMP + COUPLING CCT + X2011M

75-75

TIME OF FLIGHTS
X2011M + 4CW800F

		WITHOUT CONSTANT DELAYS			WITH CONSTANT DELAY 5		
		GAIN	PHASE	DELAY	PHASE	DELAY	
26	M=1.27 MAX	815.22	79.13	7.2739	125.93	12.2739	46.8
	M=1.5 MIN	~~[illegible]~~ 764.43	77.51	6.7677	124.31	11.7677	
30	MAX	794.48	89.573	7.27	143.573	12.27	54
	MIN	731.47	87.117	6.6088	141.117	11.6088	
34	MAX	782.75	100.18	7.5024	161.38	12.5024	61.2
	MIN	707.03	96.65	6.6702	157.85	11.6702	
38	MAX	779.21	111.304	7.9939	179.704	12.9939	68.4
	MIN	690.45	106.444	6.9759	174.844	11.6759	
42	MAX	781.89	123.34	8.7721	198.94	13.7721	75.6
	MIN	680.2	116.872	7.5555	192.412	12.5555	
46	MAX	786.65	136.71	9.8427	219.51	14.8427	82.8
	MIN	673.21	128.342	8.4214	211.142	13.4214	
50	MAX	785.71	151.79	11.12	241.79	16.12	90
	MIN	663.87	141.236	9.5105	231.236	14.5105	
54	MAX	767.08	168.7	12.317	265.9	17.317	97.2
	MIN	643.5	155.73	10.557	252.93	15.557	

Cascode Amp + Coupling NTWK + X2011Y CCT

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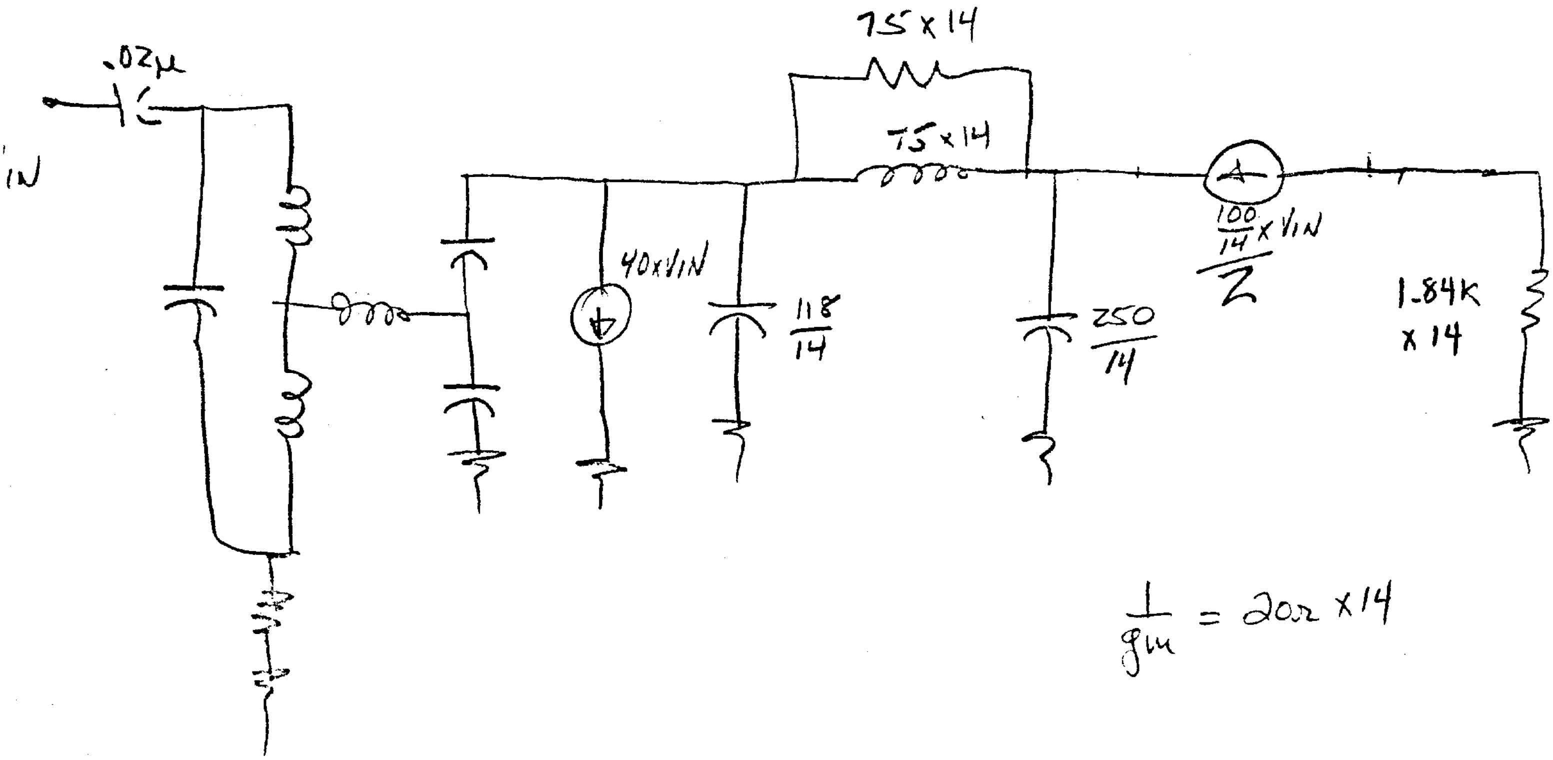
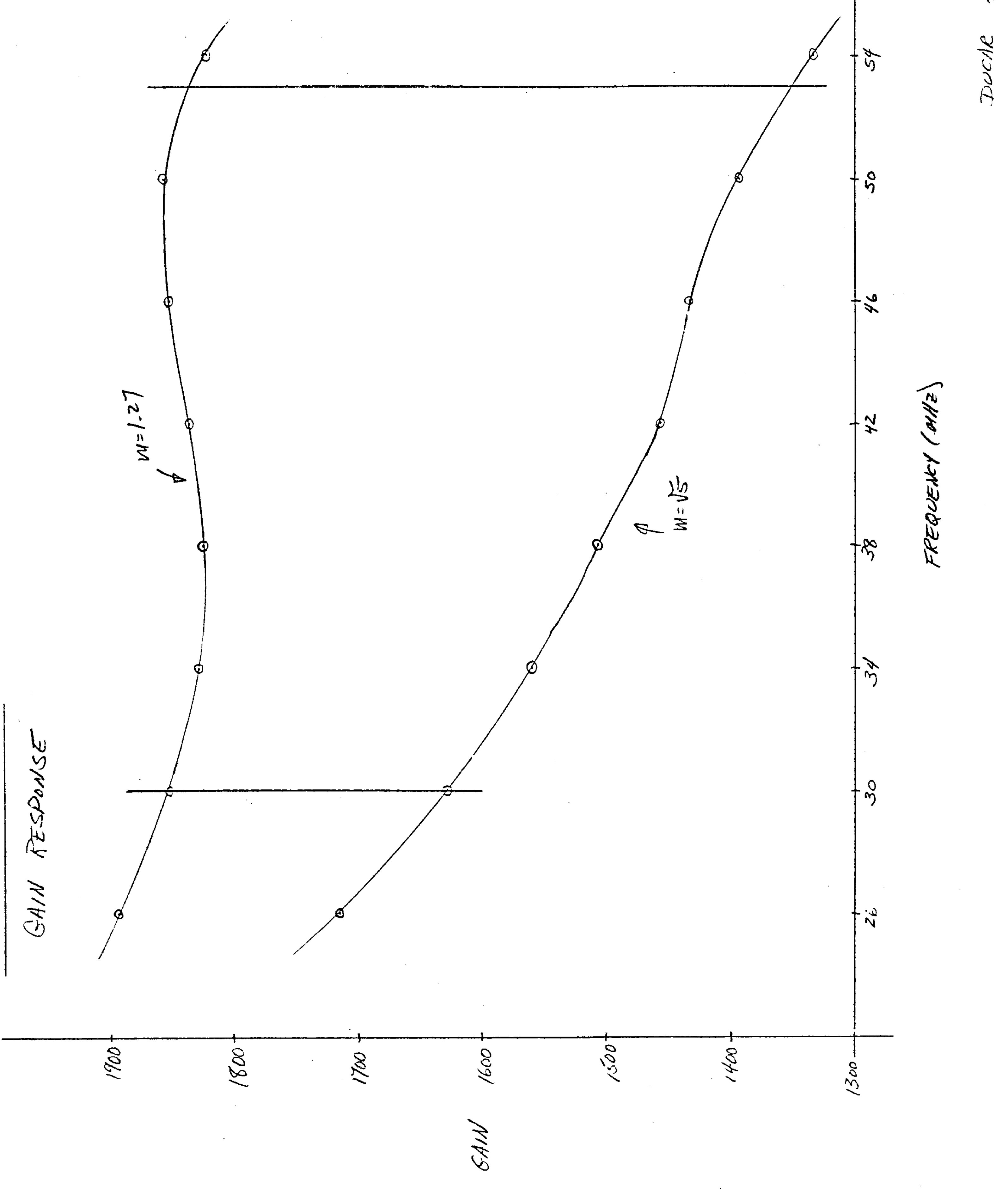
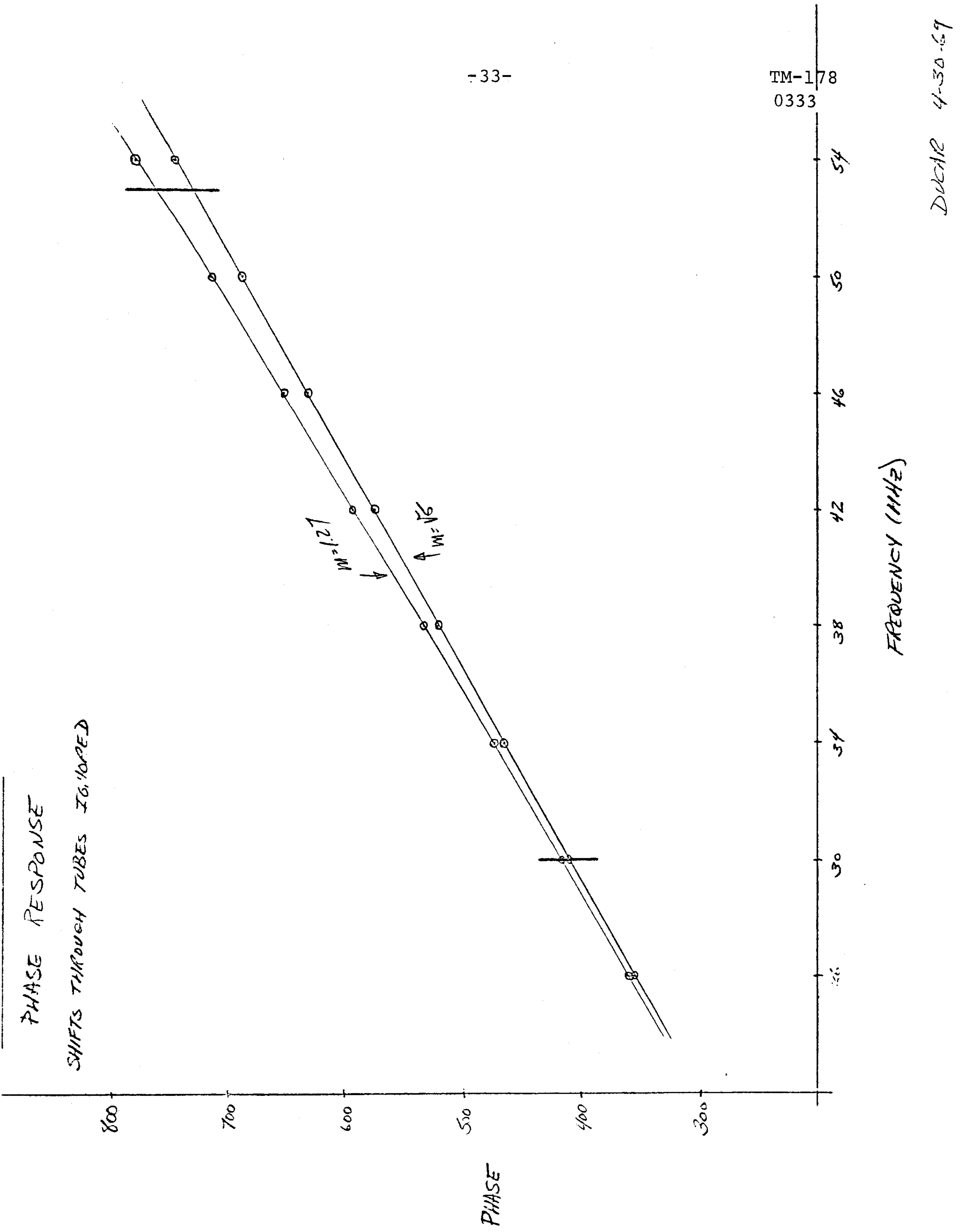
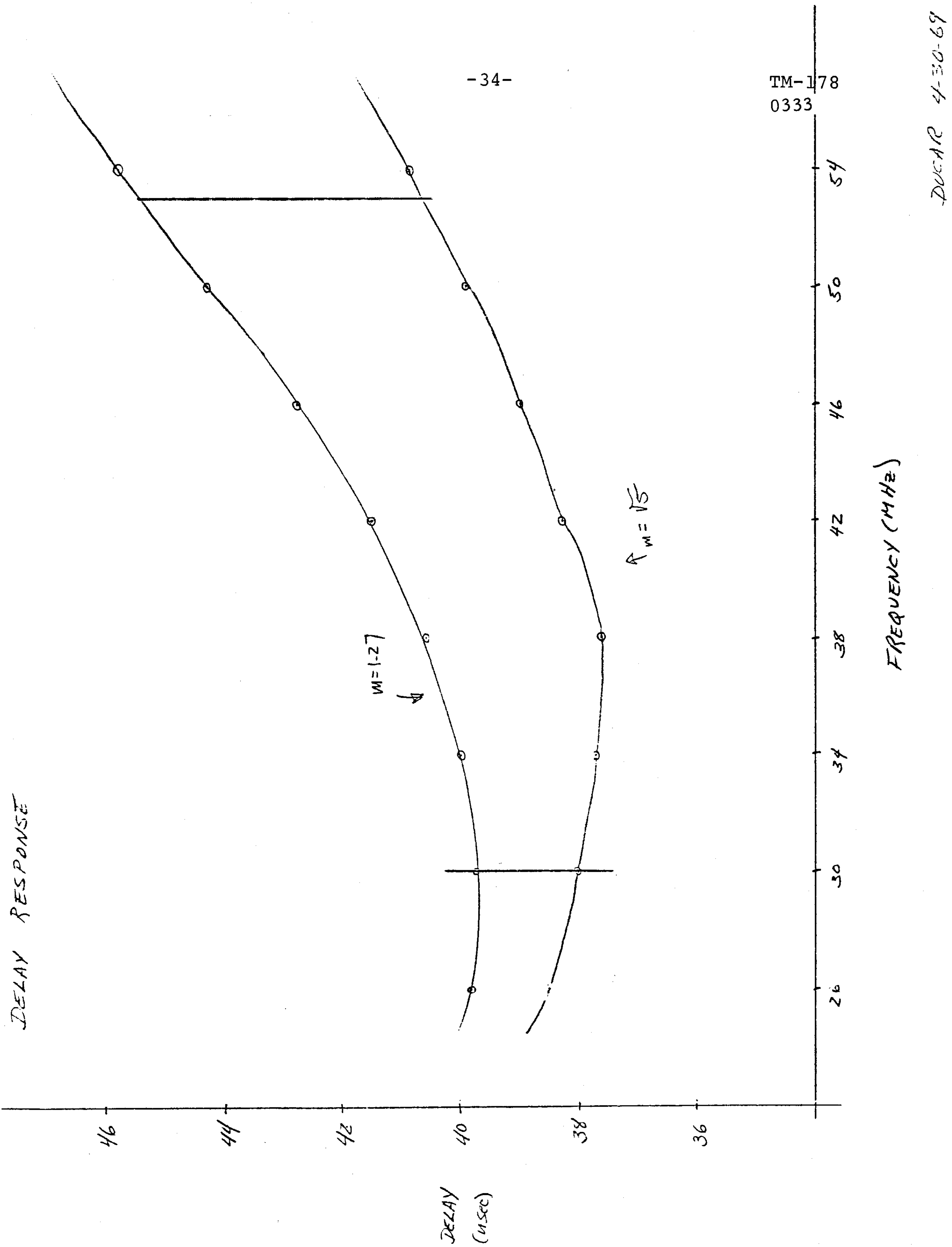


$$\frac{1}{g_m} = 20\Omega \times 14$$


GAIN RESPONSE
W=1.27
W=√5
GAIN
1900
1800
1700
1600
1500
1400
1300
26
30
34
38
42
46
50
54
FREQUENCY (MHz)
DUCAR 4-30-67


PHASE RESPONSE
SHIFTS THROUGH TUBES
W=1.27
FREQUENCY (MHz)
30
34
38
42
46
50
54
PHASE
800
700
600
500
400
300
DUCAR 4-30-69


DELAY RESPONSE
DUCAR 4-30-69
DELAY (usec)
46
44
42
40
38
36
FREQUENCY (MHz)
26
30
34
38
42
46
50
54
m=1.27
m=√5

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COMPLETE RF AMP PACKAGE

From DA input Xformer to anode of X2011A

PHASE SHIFTS THRU TUBES IGNORED

15

1894.68541	360.3465	39.83772	140.4
1716.153	356.1775	38.54942	
1853.487	417.6006	39.74345	162
1630.2045	411.3986	38.04485	
1830.9407	474.9752	39.99713	183.6
1560.4499	465.9942	37.83973	
1827.58	532.96186	40.58906	205.2
1507.235	520.50086	37.62426	
1839.1577	592.22211	41.52727	226.8
1467.258059	575.53711	38.31077	
1855.4124	650.7284	42.78394	248.4
1432.9443	630.9834	39.00284	
1860.63	715.4505	44.33858	270
1394.298	687.7995	39.93248	
1823.629	780.4066	45.83094	291.6
1332.764	745.9986	40.86164	

MISC FLAT DELAY TIMES

DA TIME OF FLIGHT — 2 ns

DA OUTPUT XFORMER CABLE - 6.5 ns

CASCODE AMP TIME OF FLIGHT - 2 ns

X2011M TIME OF FLIGHT - 3 ns

DA INPUT CABLE - 1.5 ns

15 ns

(PER NSEC DELAY PER MHz)

$$T = -\frac{d\phi(\omega)}{d(\omega)} \qquad \phi(0) = 0$$

$$1E\text{-}9 = -\frac{d\phi(\omega)}{d\omega}$$

$$1E\text{-}9 \int_0^{2\pi 1E6} d\omega = -\int_0^{2\pi 1E6} \phi(\omega)$$

$$1E\text{-}9\,(2\pi\, 1E{+}6) = -\phi(2\pi\, 1E6) \qquad \text{(change sign)}$$

$$2\pi \times 10^{-3} = \phi(2\pi 1E6) \qquad \text{(RADIANS)}$$

$$2\pi \times 10^{-3}\ \frac{180}{\pi} = \phi(2\pi E6) \qquad \text{(DEGREES)}$$

$\therefore$ +.36° shift per nSEC DELAY PER 1 MHz

COMPLETE AMP EXCEPT FOR CASCODE

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2.32414			234.4165	27.56382
2.24501			231.8675	26.781720
2.332956			274.0276	27.47345
2.228669			270.2816	26.43605
2.339113			313.5952	27.49533
2.207049			308.1442	26.16953
2.345427			353.25786	27.59516
2.182975			345.65686	25.94836
2.352195			393.28211	27.75517
2.157098			383.06511	25.75527
2.358625			431.2184	27.94124
2.128525			419.5414	25.58144
2.368058			473.6605	28.21858
2.100258			456.5635	25.42198
2.377365			514.5066	28.51394
2.071118			493.6686	25.27464

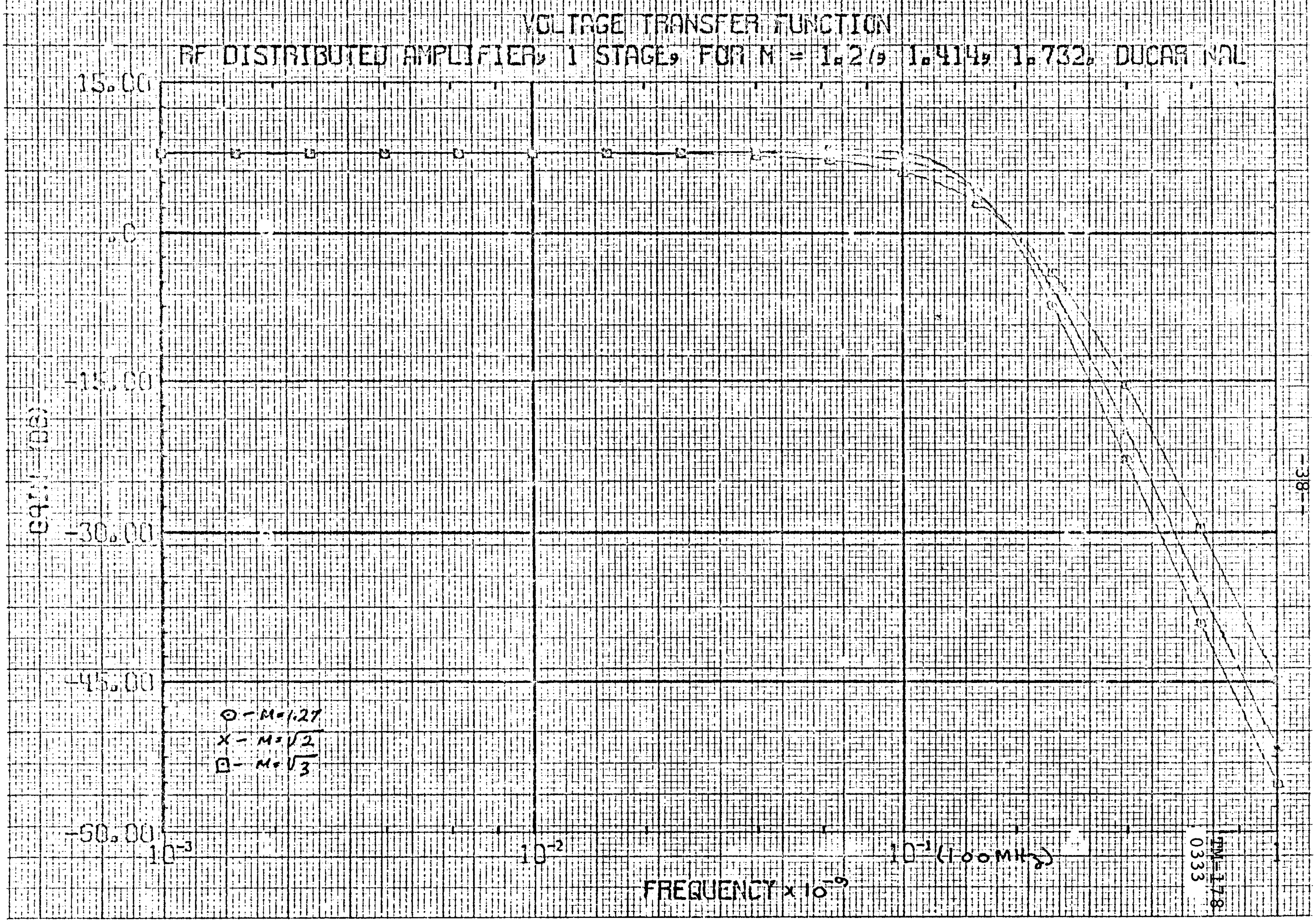

FIG-1

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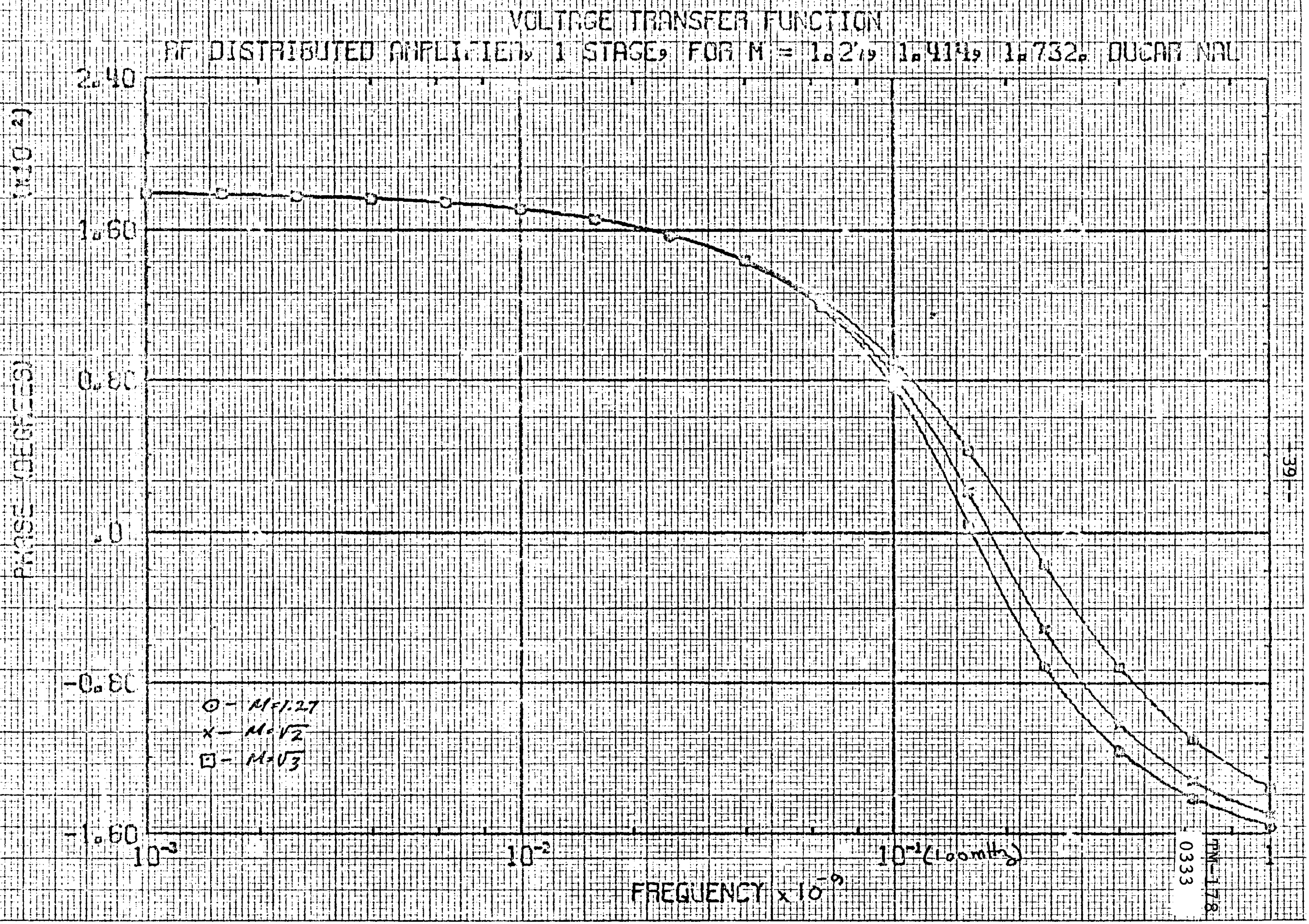

FIG - 2

VOLTAGE TRANSFER FUNCTION
RF DISTRIBUTED AMPLIFIER, 1 STAGE, FOR M = 1.27, 1.414, 1.732, DUCAR NAL

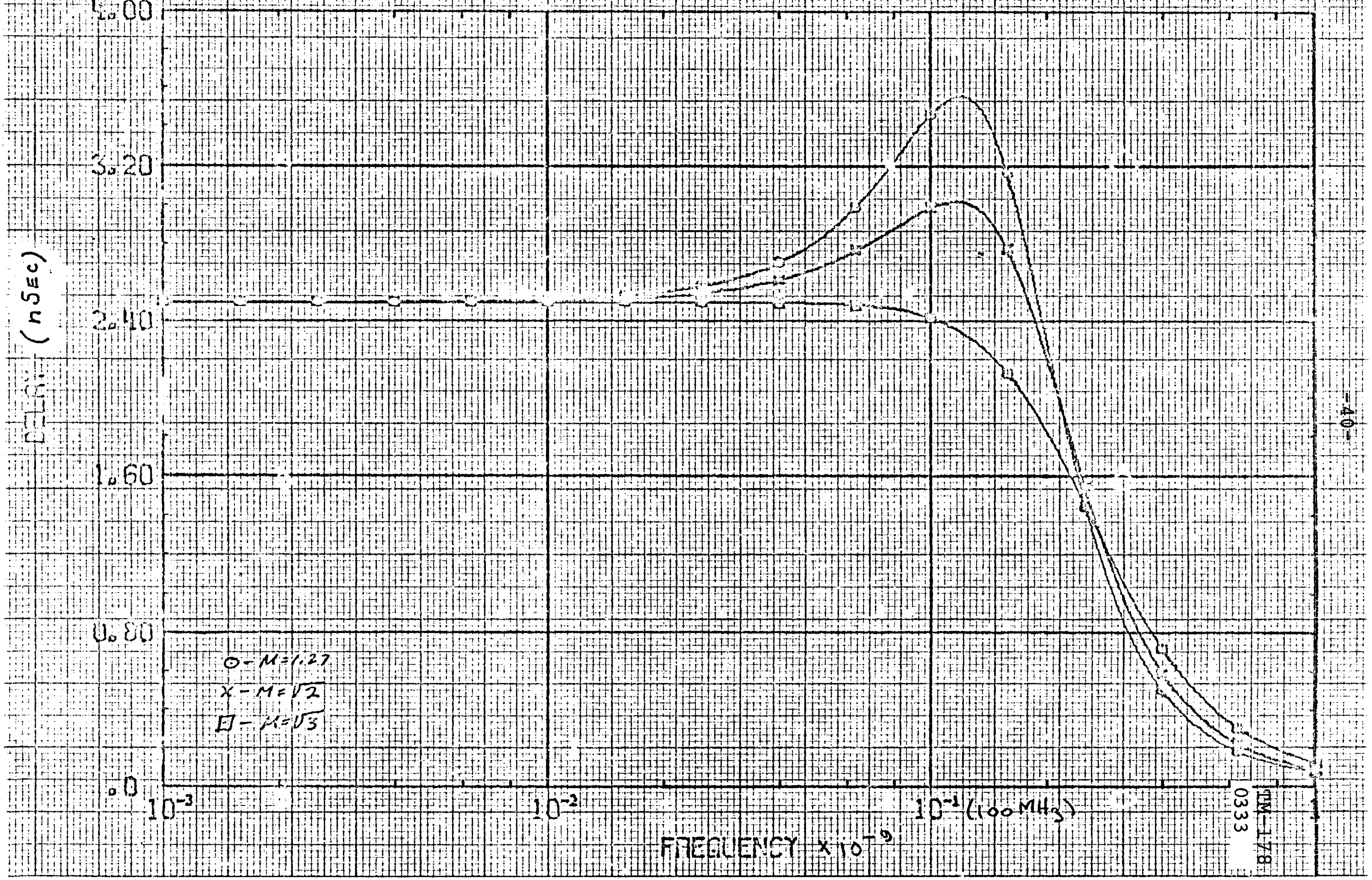

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FIG - 3

POWER SUPPLIES FOR THE RF POWER AMPLIFIER

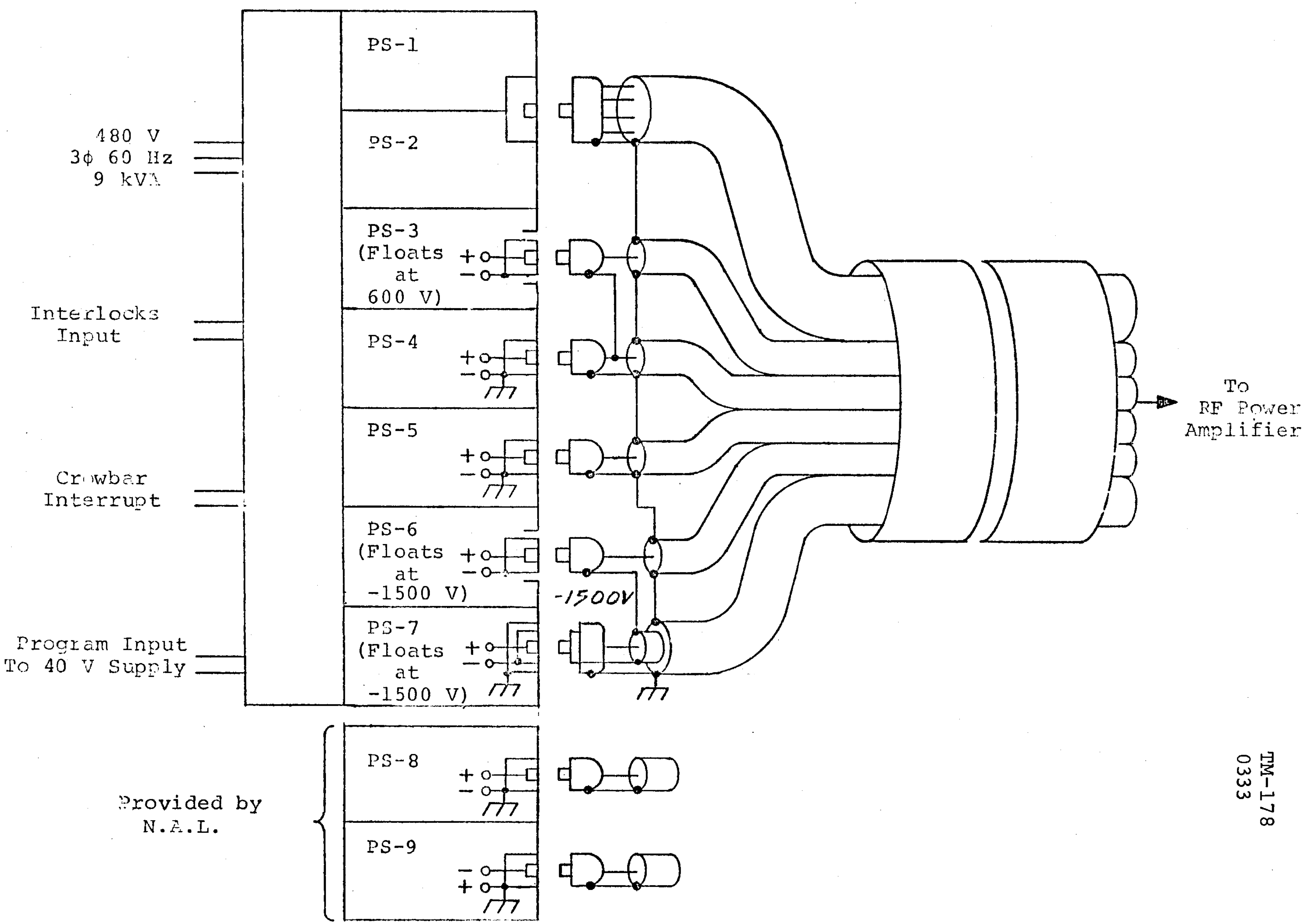

FIG. 4

RF POWER AMPLIFIER SUPPLIES

SUPPLIED BY MANUFACTURER

P.S. #	DESCRIPTION	V_{Volts}	I_{Amps}	kW	REGULATION AGAINST POWER LINE DISTURBANCE OF ±7%	REGULATION AGAINST LOAD VARIATIONS	RIPPLE
1	Adjustable, Filament Transformer Supply for 4CW100,000E Constant Voltage Transformer	360-480 (RMS)	8.0	~4 kW	±1%	-1%	Not Applicable
2	Filament Transformer Supply for 4CW800F Constant Voltage Transformer	480 (RMS)	2.0	~1 kW	±1%	-1%	Not Applicable
3	Screen Grid Supply for 4CW100,000E (Supply Common Floats at +600 V)	400 (dc)	1.0	~400 W	±1%	±1%	0.2%
4	Anode Supply for Distributed Amplifier	600 (dc)	4.5	~2.75 kW	±1%	±1%	0.2%
5	Screen Grid Supply for Distributed Amplifier (Zener from P.S. 4)	326 (dc)	0.25	Not Applicable	±0.1%	±0.1%	0.02%
6	Screen Grid Supply for the Cascode Driver (Floats at -1500 V)	335 (dc)	0.5	~200 W	±0.1%	±0.1%	0.02%
7	Programmable Grid Bias Supply for the Cascode Driver (Supply Common Floats at -1500 V)	40 (dc)	0.1	~20 W	±0.1%	±0.1%	0.02%

SUPPLIED BY NAL

8	Anode Supply (PS & Modulator)	25 kV at 10 A
9	Cathode Supply for the Cascode Driver	-1500 V at 10 A

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Figure 5